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The Coast of Bays: Paleozoic Tectonic Evolution of the Gander Margin and Adjacent Avalonia in Southeastern Newfoundland

Cees van Staal, Giorgio Ruberti, Andrew Kerr and James Conliffe

Field Trip Guide and Background Material

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THE COAST OF BAYS: PALEOZOIC TECTONIC EVOLUTION OF THE GANDER MARGIN AND ADJACENT AVALONIA IN SOUTHEASTERN NEWFOUNDLAND

Cees van Staal[1], Giorgio Ruberti[2], Andrew Kerr[3] and James Conliffe[3]

[1]Geological Survey of Canada, 625 Robson Street, Vancouver, BC V6B 5J3

[2]Department of Earth Sciences Memorial University of Newfoundland, St. John's Newfoundland, Canada A1B 3X5

[3]Geological Survey, Department of Natural Resources, PO Box 8700, St. John's, NL, A1B 4J6.

Cover photo: The dramatic coastlines of the Baie D'Espoir area, southern Newfoundland (photo: D. Brushett)

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ABOUT THIS FIELD TRIP

The region around Baie d'Espoir and northern Fortune Bay, known colloquially as the "Coast of Bays" has long been on the agenda for GAC-NL field trips, and was previously visited on trips in the late 1970s and early 1980s, when the logistics were more complex than those of today. In the 30 years that followed these trips, our knowledge of the evolution of the Appalachians in Newfoundland has grown by leaps and bounds, and our interpretative models are more detailed by at least an order of magnitude. However, our knowledge of the later episodes in the Appalachian-Caledonian Wilson Cycle – in particular the Silurian-Devonian Acadian Orogeny – remains vague compared to what we now know about Ordovician events. The Baie d'Espoir and northern Fortune Bay area is critical to understanding these events, with a major fault system separating regions now known as Ganderia and Avalonia which retain evidence for complex Paleozoic deformation and magmatism,. It is in this context that the established relationships and map patterns are re-evaluated and re-assessed in the light of new geochronological data and a more focused examination of Paleozoic rocks in Avalonia. Like many previous GAC-NL field trips, it is not our intention to present one interpretation as if it were fact, but rather to foster discussion about multiple possibilities and missing information that might be acquired through future work.

In addition to its geological interest, this is a scenically spectacular part of our province, with high rugged hills, deep fiords and picturesque communities. It is admittedly somewhat remote and little-known as a destination, and we are happy to offer a field trip that will expose a new audience to its physical beauty and scientific challenges.

ACKNOWLEDGEMENTS

The organization of field trips is both a scientific and a logistical challenge, and it has some financial aspects to it as well. The support of the Geological Survey of Newfoundland and Labrador (part of the Department of Natural Resources) in terms of time and organization, support for participation, and assistance with vehicle support is gratefully acknowledged. Without this, such ventures could rarely happen. The Department of Earth Sciences at Memorial University provided valuable subsidies to encourage student participation, which is an important aspect of these excursions. GAC-NL also wishes to acknowledge direct financial support for the 2014 trip from Anaconda Mining Inc. (operators of the Pine Cove gold mine) and from the Geoscience Education Trust of Newfoundland and Labrador (GET-NL), established from revenues accrued from National GAC-MAC meetings in 1988, 2001 and 2012. GET-NL previously operated under the name "St. John's 88-01 Trust Fund" but has now been rebranded.

Assistance from the staff at the Vancor Motel in Baie d'Espoir is greatly appreciated, as is the culinary expertise and fresh fish supplies of April's Place in English Harbour West, Fortune Bay. Editorial assistance from Chris Pereira with the final version of this field trip guide is greatly appreciated. Steve Colman-Sadd is thanked for generously sharing his knowledge of local geology and problems throughout the planning and execution of the field trip. We hope that this will become a useful document relating to Newfoundland geology, as many other guides of its type have eventually proven to be.

SAFETY INFORMATION

General Information

The Geological Association of Canada (GAC) recognizes that its field trips may involve hazards to the leaders and participants. It is the policy of the Geological Association of Canada to provide for the safety of participants during field trips, and to take every precaution, reasonable in the circumstances, to ensure that field trips are run with due regard for the safety of leaders and participants. GAC recommends steel-toed safety boots when working around road cuts, cliffs, or other locations where there is a potential hazard from falling objects. GAC will not supply safety boots to participants. Some field trip stops require sturdy hiking boots for safety. Field trip leaders are responsible for identifying any such stops, making participants aware well in advance that such footwear is required for the stop, and ensuring that participants do not go into areas for which their footwear is inadequate for safety. Field trip leaders should notify participants if some stops will require waterproof footwear.

The weather in Newfoundland in September is unpredictable, and participants should be prepared for a wide range of temperatures and conditions. Always take suitable clothing. A rain suit, sweater, and sturdy footwear are essential at almost any time of the year. Gloves and a warm hat could prove invaluable if it is cold and wet, and a sunhat and sunscreen might be just as essential. It is not impossible for all such clothing items to be needed on the same day.

Above all, field trip participants are responsible for acting in a manner that is safe for themselves and their co-participants. This responsibility includes using personal protective equipment (PPE) when necessary (when recommended by the field trip leader or upon personal identification of a hazard requiring PPE use). It also includes informing the field trip leaders of any matters of which they have knowledge that may affect their health and safety or that of co-participants. Field Trip participants should pay close attention to instructions from the trip leaders and GAC representatives at all field trip stops. Specific dangers and precautions will be reiterated at individual localities.

Specific Hazards

Some of the stops on this field trip are in coastal localities. Access to the coastal sections may require short hikes, in some cases over rough, stony or wet terrain. Participants should be in good physical condition and accustomed to exercise. The coastal sections contain saltwater pools, seaweed, mud and other wet areas; in some cases it may be necessary to cross brooks or rivers. There is a strong possibility that participants will get their feet wet, and we recommend waterproof footwear. We also recommend footwear that provides sturdy ankle support, as localities may also involve traversing across beach boulders or uneven rock surfaces. On some of the coastal sections that have boulders or weed-covered sections, participants may find a hiking stick a useful aid in walking safely.

Coastal localities present some specific hazards, and participants MUST behave appropriately for the safety of all. High sea cliffs are extremely dangerous, and falls at such localities would almost certainly be fatal. Participants must stay clear of the cliff edges at all times, stay with the field trip group, and follow instructions from leaders. Coastal sections elsewhere may lie below cliff faces, and participants must be aware of the constant danger from falling debris. Please stay away from any overhanging cliffs or steep faces, and do not hammer any locations immediately beneath the cliffs. In all coastal localities, participants must keep a safe distance from the ocean, and be aware of the magnitude and reach of ocean waves. Participants should be aware that unusually large “freak” waves present a very real hazard in some areas. If you are swept off the rocks into the ocean, your chances of survival are negligible. If possible, stay on dry sections of outcrops that lack any seaweed or algal deposits, and stay well back from the open water. Remember that wave-washed surfaces may be slippery and treacherous, and avoid any area where there is even a slight possibility of falling into the water. If it is necessary to ascend from the shoreline, avoid unconsolidated material, and be aware that other participants may be below you. Take care descending to the shoreline from above.

Other field trip stops are located on or adjacent to roads. At these stops, participants should make sure that they stay off the roads, and pay careful attention to traffic, which may be distracted by the field trip group. Participants should be extremely cautious in crossing roads, and ensure that they are visible to any drivers. Roadcut outcrops present hazards from loose material, and they should be treated with the same caution as coastal cliffs; be extremely careful and avoid hammering beneath any overhanging surfaces.

The hammering of rock outcrops, which is in most cases completely unnecessary, represents a significant “flying debris” hazard to the perpetrator and other participants. For this reason, we ask that outcrops not be assaulted in this way; if you have a genuine reason to collect a sample, inform the leaders, and then make sure that you do so safely and with concern for others. Many locations on trips contain outcrops that have unusual features, and these should be preserved for future visitors. Frankly, our preference is that you leave hammers at home or in the field trip vans.

Subsequent sections of this guidebook contain the stop descriptions and outcrop information for the field trip. In addition to the general precautions and hazards noted above, the introductions for specific localities make note of specific safety concerns such as traffic, water, cliffs or loose ground. Field trip participants must read these cautions carefully and take appropriate precautions for their own safety and the safety of others.

PART 1: BACKGROUND MATERIAL

INTRODUCTION

Overview of the fieldtrip

This three day field trip will mainly focus on the geology of the Avalonian rocks in northern Fortune Bay, and the adjacent Ganderian rocks situated between the Hermitage Bay fault and the Baie d'Espoir area (Figure 1; Figure 2). The terms "Ganderia" and "Avalonia" are to a large extent (but not completely) synonymous with the Gander and Avalon zones in the original terminology of Williams (1979). Emphasis is placed on the effects, regional distribution and tectonic setting of the Salinic and Acadian orogenies in this part of Newfoundland. In addition, we will make a few stops along the Baie d'Espoir highway including parts of the Early-Middle Cambrian Coy Pond-Great Bend ophiolite (Kean, 1974; Colman-Sadd and Swinden, 1982; Sandeman et al., 2012) and other miscellaneous localities of geological interest.

The Paleozoic provenance and tectonic relationships between Avalonia and Ganderia remain one of the outstanding problems in Appalachian geology. Recent studies were conducted in this area as part of TGI-4 by the Geological Survey of Canada, in conjunction with work by the Geological Survey of Newfoundland and Labrador (GSNL). Current work by GSNL is aimed largely at Quaternary geology and till geochemistry (D. Brushett, unpublished), but the area was of interest in the context of previous regional projects investigating granitoid magmatism (e.g., Kerr et al., 1995; Kerr, 1997), and geological mapping in Avalonia east of the Hermitage Bay fault (e.g., O'Brien et al., 1996, O'Brien, 1998). Mapping in the metamorphic and igneous rocks of Ganderia west of the fault was completed in the late 1970s and early 1980s, and is summarized by Colman-Sadd and Swinden (1982) and Colman-Sadd (1979, 1985). The current TGI-4 project in Newfoundland is intended to better document and understand the tectonic evolution of Ganderia and Avalonia during the Silurian and Devonian, and unravel the details of their interaction. This will also improve our knowledge of the tectonic setting responsible for the formation of Late Silurian and Devonian magmatic rocks, and accompanying mineralization, and hopefully also outline new targets for exploration.

Regional Setting and General Geology

The area of the field trip lies in south-central Newfoundland, and encompasses parts of Baie d'Espoir, Hermitage Bay, and northern Fortune Bay; inland areas along the Baie d'Espoir highway are mostly part of the Gander River drainage basin. In the zonal terminology of Williams (1979) this includes the southwestern Avalon Zone and parts of the Gander Zone and structurally overlying Dunnage Zone (Exploits Subzone), In the synthesis of Williams et al. (1988), the Dunnage Zone rocks were viewed as tectonically juxtaposed above the largely metasedimentary rocks of the Gander Zone, with the latter forming several prominent tectonic "windows" (Figure 1). Although not exposed within the field trip area, Neoproterozoic (Ediacaran) plutonic and volcanic rocks are present in central Newfoundland, and a basement of similar character is inferred to exist at depth throughout the eastern part of the Central Mobile Belt (Figure 1; Figure 2). To the southeast of the Hermitage Bay fault, the geology is dominated by Neoproterozoic volcanic, sedimentary and plutonic rocks that have a complex history, and which are overlain by sedimentary rocks of latest Ediacaran to Cambrian age. The youngest sedimentary rocks in the area are shallow-marine to terrestrial sequences of Devonian age, which are of local extent but are potentially important in understanding tectonic evolution.

Granitoid rocks are abundant on both sides of the Hermitage Bay fault (Figure 2). To the northwest, these are of largely Paleozoic age (Silurian to Devonian), but east of the fault there are several generations ranging in age from Neoproterozoic (~ 620 Ma) to middle Devonian (~ 375 Ma). Not all such granitoid rocks are dated, and field characteristics or geochemistry alone are not sufficient to distinguish them from one another, The large Ackley Granite, dated at 380 – 377 Ma (O'Brien, 1998; Lynch et al., 2009) crosscuts the Hermitage Bay fault and is traditionally regarded as a 'stitching pluton' that constrains the final amalgamation of the bounding terranes.

The deformation histories on both sides of the Hermitage Bay fault are complex, and various aspects of these events form a major focus for this field trip.

OVERVIEW OF GEOLOGY AND OUTSTANDING PROBLEMS

Geological Background

The rocks of the Gander Zone and intimately associated parts of the Dunnage Zone (Exploits subzone) share at least in part, a common provenance and Proterozoic basement (see above) and will be referred to herein as Ganderia. The rocks of the Avalon Zone will be referred to herein as Avalonia (cf. van Staal and Barr, 2012 and references therein). Avalonia and Ganderia are two Gondwanan-derived terranes that originated on different parts of the eastern margin of the Iapetus Ocean and travelled across Iapetus to arrive at the margin of composite Laurentia during the Early and Late Silurian respectively (van Staal et al., 2012; Figures 3 and 4). These two terranes are separated by the Dover-Hermitage Bay fault system in Newfoundland (Figures 2 and 3). This fault zone is a major structure that at least locally appears to cut the entire lithosphere along its northern extension (Keen et al., 1986). The Dover fault zone accommodated both strike-slip as well southeast-directed oblique reverse movements (Holdsworth, 1994; van der Velden et al., 2004). The Paleozoic evolution of Ganderia and Avalonia is markedly different until the late Early Devonian, when red sandstones and conglomerates (a molasse sequence termed the "Old Red Sandstone" in the British Caledonides) overstepped onto Avalonia (Figure 3; Williams and O'Brien, 1995; O'Brien et al., 1996; van Staal et al., 2014). This supports other lines of evidence that these terranes remained isolated from each other until their successive accretion to composite Laurentia (van Staal and Barr, 2012) . However, exactly how convergence was accommodated between Ganderia and Avalonia is poorly constrained at present, because obvious remnants of an intervening ocean have nowhere been preserved along their boundary in Newfoundland. Nevertheless, Silurian arc-like plutons and associated volcanic rocks in southern Newfoundland (e.g. ca 429 Ma Burgeo Intrusive Suite; Dickson et al., 1985; Dunning et al., 1990; Kerr et al., 1995; Kerr, 1997) suggest that subduction of intervening oceanic lithosphere is a possible model to explain convergence and amalgamation of these terranes (Figure 4). If so, this oceanic basin (Acadian seaway of Hibbard et al., 2006; van Staal et al., 2009) was probably narrow, because arc-backarc magmatism associated with its closure was relatively short-lived (Dunning et al., 1990; O'Brien et al., 1991). Subduction-driven convergence and collision between Ganderia and Avalonia also provides an attractive causative mechanism for the penetrative Late Silurian-Early Devonian Acadian orogeny between 419 and 395 Ma (van Staal et al., 2009; Figure 4). Old and dense oceanic lithosphere is generally not expected to be preserved during terrane convergence driven by subduction. Hence, the absence of preserved remnants is not definitive evidence against the former existence of oceanic crust between Ganderia and Avalonia. For example, all that is left of the Luzon arc-China convergence in the collision zone in central Taiwan is a strongly-deformed accretionary prism, mainly made up of sedimentary rocks scraped off from the down-going Eurasian continental margin. The latter was juxtaposed in central Taiwan against rocks forming part of the Luzon arc-forearc system built upon the overriding Philippine Sea plate. No igneous rocks representing the intervening South China Sea oceanic lithosphere have been preserved and most of the forearc terrane was probably underthrusted beneath the Luzon arc (Tang and Chemenda, 2000). This model of subduction-related convergence through consumption of a narrow oceanic realm (seaway) provides a working model (Figures 4 and 5) that can be tested through detailed geological studies.

Ganderia: Geology and Evolution

The geological elements of Ganderia vary from west to east (Figures 2 and 3; Figure 7). In the west, it comprises Cambrian-Ordovician ensialic island arc sequences and associated sedimentary rocks (e.g. Victoria Lake Supergroup), which formed on a Late Ediacaran volcanic-plutonic substrate (Rogers et al., 2006; Zagorevski et al., 2010). In the east, it is dominated by Cambrian-Ordovician sedimentary and associated minor volcanic rocks (mainly felsic) that collectively define the Gander margin (see further discussion below) (Colman-Sadd, 1980; van Staal, 1994). Inheritance and isotope studies combined with relationships established in other parts of the Canadian Appalachians suggest that the Gander margin is underlain by Proterozoic basement containing rocks of a similar nature to those known to be present beneath the Paleozoic island arc sequences further to the west (Kerr et al., 1995; van Staal and Barr, 2012 and references therein; Figure 3). Both halves of Ganderia are also characterised by similar Lower to Middle Ordovician (Floian-Darriwilian) fossil faunas (Williams et al., 1995; Harper et al., 2009). For reference purposes, the various stratigraphic subdivisions and absolute ages for Lower Paleozoic periods and their boundaries are indicated in Table 1; this guide uses the International Commission on Stratigraphy (ICS) terminology, rather than subdivisions based upon the DNAG time scale (Palmer, 1984), employed in most older publications. Models for the evolution of Ganderia during the Lower Paleozoic are suggested in Figure 6. Figure 7 summarizes the geological units and the field trip stops.

In southeastern Newfoundland, the Gander margin is dominated by Cambrian-Ordovician marine sedimentary rocks, which were metamorphosed from greenschist facies to upper amphibolite facies conditions, and locally formed migmatites suggestive of partial melting processes. These rocks have been divided into the Baie d'Espoir Group and the Little Passage gneiss, which are separated by the Day Cove fault (Colman-Sadd, 1976; 1980). The Little Passage gneiss is thought to represent the high-grade and migmatised equivalents of the Baie d'Espoir group (Blackwood, 1985), consistent with the presence locally of coticule beds and pyritiferous schist of probable volcanogenic origin in paragneisses. However, it may also include some high-grade equivalents of the quartz-rich sandstones and shales of the Gander Group, which is located along strike to the northeast.

The Ordovician Baie d'Espoir Group ranges in age from Lower Ordovician (Floian) to Upper Ordovician (Katian). on the basis of sparse fossil evidence; this corresponds to a range in age from ~ 479 Ma to ~ 456 Ma. It mainly comprises a series of sandstones, siltstones and shales, in part representing deep water turbidites (Colman-Sadd, 1980), which together with correlatives along strike (e.g. Davidsville Group) in turn unconformably to conformably overlie Cambrian to Lower Ordovician (?) metasandstones and shales of the Gander Group (O'Neill and Blackwood, 1989; Colman-Sadd et al., 1992; Valverde-Vaquero et al., 2006). Both units were interpreted to have been deposited on a northwest-facing (present coordinates) continental margin by Colman-Sadd (1980), which is consistent with the nature of the sedimentary rocks and paucity of volcanic rocks in both the Gander and Baie d'Espoir groups and correlatives elsewhere (van Staal et al., 1996; van Staal and Barr, 2012). For this reason these rocks were collectively termed the Gander margin by van Staal (1994; 2007). Passive margin sedimentation was interrupted for a short period during the earliest Ordovician (Tremadocian-Floian; 483 – 478 Ma), at least in the western parts of the Gander margin, by the obduction of ophiolites such as the Coy Pond and Pipestone Pond complexes onto the Gander Group (Colman-Sadd et al., 1992). This event is now generally termed the Penobscot Orogeny (Figure 6), and is broadly synchronous with the better-known Taconic events on the Laurentian margin of Iapetus. Passive margin sedimentation terminated during the Late Ordovician and Early Silurian and was replaced by marine foreland basin deposits following the onset of Salinic tectonism (van Staal and Barr, 2012; van Staal et al., 2014). It is significant that volcanic-derived sandstones in the Baie d'Espoir Group (North Steady Pond Formation) become more pronounced and coarsen upwards towards the northwest (Colman-Sadd, 1980), which suggests that the Gander margin probably represents the passive margin of a backarc rather than a true oceanic basin throughout its history. This back-arc basin (Jenner and Swinden, 1993; Zagorevski et al., 2008; 2010) was sandwiched between the Cambrian- to Middle Ordovician (515-458 Ma) island arc volcanic rocks such as the Victoria Lake Supergoup at the northwestern (leading) edge of Ganderia and the Gander margin to the southeast. The short-lived Penobscot obduction destroyed most evidence of the Cambrian-Early Ordovician opening phase of the back-arc basin adjacent to the Gander margin, but back-arc rifting and spreading resumed after 476 Ma and led to the opening of the Exploits back-arc basin (Figure 4). These latter events were concurrent with deposition of the Baie d'Espoir Group and its correlatives (e.g. Davidsville and Harbour Le Cou groups) on its passive southeast margin (van Staal, 1994; Schofield et al., 1997; Valverde-Vaquero et al., 2006; Zagorevski et al., 2010).

Closure of the Exploits backarc basin eventually led to Late Ordovician - Early Silurian accretion of the Gander margin to composite Laurentia, which subjected the Baie d'Espoir Group and its underlying basement to the Salinic orogeny (Figure 4). The Salinic orogeny in southeastern Newfoundland culminated in formation of the Little Passage gneiss and generation of spatially associated syn-tectonic biotite-bearing granitoid rocks between 423 and 421 Ma. Observations by CVS and GR confirmed that unfoliated veins of the K-feldspar porphyritic Gaultois granite (421 ± 2 Ma) cut foliated tonalitic and granodioritic veins and neosomes that make up the bulk of the migmatitic phase of the Little Passage gneiss dated at $423^{+5}/_{-3}$ Ma (Colman-Sadd, 1976; Dunning et al., 1990). The Salinic orogeny was thus in its waning stages when the Gaultois granite intruded, which is consistent with age relationships deduced in northeastern Newfoundland (van Staal et al., 2014).

The products of Salinic deformation and metamorphism (D_1-M_1) in turn were overprinted by structures generated during the Early Devonian Acadian orogeny (Figures 3 and 4). The Acadian tectonism led to SE-vergent D_2 folds, sinistral oblique SE-directed reverse faults (e.g. Day Cove fault) and low- to medium-pressure metamorphism (M_2), which is coeval with generation of syn-to post D_2 biotite-muscovite granites (Colman-Sadd, 1976, 1979, 1980;

Piasecki, 1988) of the Early Devonian (417-396 Ma) North Bay granite suite (Dickson, 1990; Dunning et al., 1990). D_2-related shear localised in ductile faults (e.g. Day Cove fault) caused retrogression of high-grade metamorphic assemblages in the shear zones and emplaced relatively low-grade (biotite zone) Acadian metamorphic tectonites above higher-grade gneisses and schists of the Little Passage gneiss that record the earlier Salinic Orogeny (Colman-Sadd, 1976; Piasecki, 1988). Shear sense indicators observed by CVS and GR are consistent with the structural interpretations of Piasecki (1988) that the Day Cove fault probably accommodated a reverse component of movement in addition to sinistral strike-slip shear. The accumulated finite strain led to intense flattening, marked by “chocolate-tablet” boudinage (see later field stop descriptions) in the sheared rocks, which suggests that movements may have been polyphase and complex. This phase of shearing followed earlier exhumation of the high-grade Salinic metamorphic rocks and probably took place late during D_2. These relationships are consistent with a model in which the Salinic and Acadian orogenies represent two kinematically-unrelated tectonic events, separated by a phase of latest Silurian-Early Devonian uplift and exhumation (van Staal et al., 2014; Figures 3 and 4).

Western Avalonia: Geology and Evolution

The Avalonian rocks of the northern Fortune Bay area (Figures 8 and 9) comprise a series of Cryogenian-Ediacaran (685-550 Ma) sedimentary and volcanic rocks; the latter are considered to be predominantly arc-related. In ascending order, these rocks are assigned to the Tickle Cove Formation, the Connaigre Bay Group and the Long Harbour Group and associated coeval intrusive suites (O’Brien et al., 1996; O’Brien, 1998). The Cryogenian (685-670 Ma) rocks of the Tickle Point Formation and Furby’s Cove intrusive suite are separated from the younger Ediacaran units by a phase of deformation that predates intrusion of ca. 620 Ma granitoid rocks of the Simmons Brook intrusive suite. Another phase of deformation locally affected these ca. 620 Ma plutonic rocks prior to intrusion of younger Ediacaran intrusive suites after 590 Ma (O’Brien et al., 1996; O’Brien, 1998). The causes and tectonic significance of the various Neoproterozoic events in Avalonia remain poorly understood, but are probably related to convergence and progressive amalgamation of the various volcanic arc terranes that together make up Avalonia. The Neoproterozoic volcanic and sedimentary rocks in the east of the Fortune Bay area are overlain by Ediacaran to Lower Paleozoic (Cambrian) sedimentary rocks of the Youngs Cove Group (Figures 8 and 9), which based on observations by CVS and GR were complexly folded and involved in thrusting prior to deposition of redbeds of the Middle to Upper Devonian Great Bay de L’Eau Formation, which in turn was deposited prior to intrusion of the Middle-Late Devonian Belleoram granite (Williams, 1971; O’Brien et al., 1996; O’Brien, 1998). The sub-middle Devonian unconformity marks the Acadian orogeny in this part of Newfoundland. Observations by CVS and GR confirm earlier conclusions by Williams and O’Brien, 1995 that Lower to Middle Devonian red beds and minor limestone of the Cinq Isles and Pool’s Cove formations were locally complexly deformed, involving Acadian upright to recumbent folding and thrusting. The red beds comprise a thick sequence of sandstone and conglomerate and probably represent the fill of a late Acadian molasse basin (van Staal et al., 2014) that captured detritus form the rising Acadian mountains in adjacent Ganderia (Williams and O’Brien, 1995; Figure 3). All data thus confirm earlier inferences (Williams, 1995 and references therein) that the Acadian Orogeny affected both Ganderia and Avalonia, even though collision-related metamorphic and igneous rocks are principally concentrated in Ganderia. These relationships support a tectonic model in which Ganderia was situated on the upper plate, as implied also by the presence of Silurian arc-type magmatic rocks in the Hermitage flexure (Figure 4). Avalonia, on the other hand, represented the lower plate during Acadian convergence and collision between these two terranes (Figure 4)

An interesting new problem is posed by geochronological data from the Pass Island granite at the southwestern tip of the Connaigre Peninsula (Figure 2), which has always been assumed to be a Devonian pluton of similar age to other prominent examples such as the Ackley Granite and Francois Granite (Kerr et al., 1993). However, a Late Silurian (ca. 423 Ma) crystallization age now forces some reconsideration of this link (Kellett et al., in press). Granitic plutons of ca. 423 Ma age are previously unknown in Avalonia in Newfoundland or Atlantic Canada, but such late Silurian magmatism is important throughout Ganderia. The age from Pass Island raises questions as to whether all of the Precambrian rocks of northern Fortune Bay are truly part of Avalonia and, if not, whether the Hermitage Bay fault actually represents the true terrane boundary along its whole length.

Hermitage Bay fault

The Hermitage bay fault is inferred to mark the Ganderia-Avalonia boundary in southeastern Newfoundland (Figures 2 and 3; Figure 7). The fault juxtaposes Upper Silurian to Lower Devonian K-feldspar-porphyritic granites such as the ca 421 Ma Gaultois granite and leucocratic granites of the Northwest Brook Complex in Ganderia against Neoproterozoic rocks of the Tickle Point Formation, Connaigre Bay Group, Simmons Brook intrusive suite and Harbour Breton granite in Avalonia (O'Brien, 1998). The fault zone is characterised by ductile-brittle chlorite-rich shears and belts of cataclasite. The absence of ductile shears in contrast to the wide zone of fault-related tectonites associated with the Dover fault along strike to the northeast (Holdsworth, 1994), suggest that different crustal levels of the structure are exposed, and that the Hermitage Bay fault accommodated mainly higher-level movements. It is also possible that ductilely sheared rocks akin to those of the Dover fault zone are largely masked in southeastern Newfoundland by granitoid rocks of the Northwest Brook Complex, which forms a composite pluton elongated along the fault zone's western margin. This is supported by evidence suggesting that the ca. 403 Ma Indian Point granite (O'Brien, 1998), (formerly called the Straddling granite; Colman-Sadd, 1980), which is a member of the Northwest Brook Intrusive Complex, intruded late into the brittle fault zone. Red aplite of the Indian Point granite cuts strongly foliated Gaultois-type granite along the western margin of Hermitage Bay, but the Indian Point granite itself is only weakly foliated or transformed into narrow zones of chlorite-bearing feldspar-porphyroclastic cataclasite along the trace of the Hermitage Bay fault. The Avalonian rocks incorporated in the Hermitage Bay fault zone on the other hand are much more penetratively deformed into cataclasite than the Indian Point granite. These observations collectively suggest that the main brittle movements accommodated by the Hermitage Bay fault zone took place before ca 403 Ma. If the strongly foliated parts of the Gaultois granite record early ductile deformation associated with development of the Hermitage Bay fault zone, movements along the had started by at least by ca. 421 Ma. The orientation of subsidiary shears, lineations and scarce shear sense indicators suggest the Hermitage Bay fault subsequently accommodated a long and complex movement history involving both strike-slip as well dip-slip motions.

PART 2: FIELD TRIP ITINERARY

The field trip itinerary is broken into two full days, followed by a partial day including selected stops enroute from Baie d'Espoir to the Trans-Canada Highway. Day One focuses on rocks within Ganderia, and terminates at outcrops representing the Hermitage Bay fault. Day Two follows the same route initially, but focuses on the area of Avalonia located southeast of the fault, around the communities of Pools Cove, Belleoram, English Harbour West and Wreck Cove. Day Three includes three general interest stops on the Baie D'Espoir highway.

Field trip stops for Day One and Day Three are indicated in Figure 7, and the field trip stops for Day Two are indicated in Figure 8. All UTM coordinates are in NAD 27, UTM Zone 21N.

Day One: A transect through Baie d'Espoir Group and Little Passage gneiss, along the Baie D'Espoir highway.

Stop 1.1: Ultramafic rocks of the Great Bend Ophiolite (UTM 611266E / 5379066N)

Join Highway 360 just east of the Exploits River bridge outside Bishop's Falls. Check to see if there is adequate fuel in the tank! Watch for moose, and also for moose hunters! Continue for about 65 km, to Stop 1.1, which is a large quarry located on the east (left) side of the road, 3.1 km south of the bridge over the Northwest Gander River.

This locality reveals varied, serpentinized, ultramafic rocks of the Great Bend ophiolite complex, one of several such units that separate the higher-grade metasedimentary rocks of the Gander Group and equivalents from volcanic and sedimentary rocks assigned to the Dunnage Zone. The emplacement of these ophiolites records the earliest Paleozoic orogenic event in the field trip area, the Ordovician Penobscot Orogeny. The timing of this event, which emplaced arc-type volcanic sequences developed within the Iapetus Ocean above the siliciclastic rocks of the Gander Group and its equivalents, is constrained by the ca. 464 Ma U-Pb ages obtained from leucocratic granites that cut both the metasedimentary rocks and the ophiolites (Colman-Sadd et al., 1992).

The ultramafic rocks here contain minor chromite, and at a nearby locality more abundant chromite and also magnesite (Magnesium Carbonate) are present. The latter is a product of hydrothermal alteration processes, and has attracted some economic evaluation. These areas of mineralogical interest within the Great Bend ophiolite will be visited on the return trip on Day Three (see Stop 3.2). Stop 1.1 is dominated by massive peridotite, and represents material from the uppermost mantle, below the Moho.

Stop 1.2: Conglomerates of the Baie d'Espoir Group (UTM 612129E / 5371402N)

These roadcut outcrops are located in roadcuts about 8.2 km south of Stop 1.1, and are described in a previous field trip guide by Colman-Sadd and Swinden (1983). The conglomerates at this locality include varied clasts of sedimentary, plutonic and volcanic rock types. The conglomerate is interpreted to be a channel fill deposit within a larger turbidite fan, i.e., not of shallow-water origin. It is closely associated with volcanogenic sandstones that resemble those seen at Stop 1.3 (see below). Although this outcrop has always been regarded as part of the Ordovician Baie D'Espoir Group, an outcrop located along strike to the northeast yielded Silurian fossils in blocks (W. L. Dickson, unpublished data) raising questions about its true age and relationships. Sedimentary rocks of the latest Ordovician to Silurian Badger and Botwood groups are present in locations to the northeast, but paucity of outcrop renders stratigraphic relationships rather uncertain, to say the least.

Stop 1.3: Twillick Brook Member of the St. Josephs Cove Formation, Baie d'Espoir Group (UTM 606001E / 5325135N)

From Stop 1.2, continue south on Route 360 for another 53.5 km, to roadcut outcrops located on the west (right) side of the road, around 1.4 km south of the bridge over Twillick Brook. The exposure continues in a gravel pit also located on the west side of the road. This stop is described in a previous guidebook by Colman-Sadd and Swinden (1983)

The Twillick Brook Member contains Dapingian-Darriwilian (468 ± 2 Ma) felsic pyroclastic rocks (e.g. quartz-feldspar crystal tuff) and represents one of the few volcanic rocks deposited on the Gander margin in this part of Newfoundland (Colman-Sadd et al., 1992). In these outcrops, the metavolcanic rocks are in contact with graphitic slates to the south, and also include sedimentary lenses. These rocks all form part of the St. Josephs Cove Formation, which mainly comprises fine grained, low energy turbidites and is conformably and gradually overlain by black shale (Colman-Sadd, 1979;1980); poorly-preserved graptolites in this were consistent with a Darriwillian-Sandbian age in current terminology (Williams et al., 1992). Significantly, the Twillick Brook Member appears to be in direct contact with the Gander Group further to the northeast (Blackwood and Green, 1982), such that the underlying turbidites are cut out, hinting that here there may be a cryptic fault, or a disconformity (or a combination of both) between the Gander and Baie d'Espoir groups. This quarry is the site of geochronology sampling by Colman-Sadd et al., 1992, who obtained an age of 468 ± 2 Ma (Darriwilian in current stratigraphic terminology).

Stop 1.4: St. Josephs Cove Formation, Trout Hole Falls Park, Head of Baie d'Espoir (UTM 595570E / 5309496N)

Continue south on Route 360 from Stop 1.3, and then turn right on Route 361 towards Head of Baie d'Espoir. Continue for 9.8 km to Trout Hole Falls Municipal Park, located on the right (west) side of the road. The outcrop is described also in the Traveller's Guide to the Geology of Newfoundland and Labrador (Colman-Sadd and Scott, 1994). Note that if time is short, this outcrop may be deferred for later in the day enroute to our overnight accommodation in Baie D'Espoir.

Prominent beds of sandstone and shale here form a natural dam, creating a lovely swimming hole and an excellent lunch stop. The beds are nearly vertical, and well-cleaved. These steeply-dipping thinly-bedded greenschist facies sedimentary rocks contain a S_1 cleavage that is nearly parallel to bedding. Both the beds and S_1 are folded into nearly symmetrical recumbent F_2 folds with a shallowly-dipping S_2 crenulation cleavage. The F_2 structures are situated near the hinge of a large SE-verging F2 fold according to Colman-Sadd (1976). The outcrop is extremely instructive in terms of understanding how complex structural patterns develop through multiple periods of deformation.

Stop 1.5: Day Cove fault (UTM 606104E / 5301520N)

From Stop 1.4, return to Route 360, and turn south. The outcrops representing the fault zone are about 26.4 km south of Stop 1.3 (if proceeding directly) or a lesser distance from the Route 360/361 junction. The outcrop is described in an earlier field trip guide by Colman-Sadd and O'Driscoll (1978); it reveals the basal fault, slide or detachment zone (or whatever you choose to call it) of the Baie D'Espoir Group.

This outcrop was visited by one of us (CvS) in 2001 with Steve Colman-Sadd and comprises mylonitic rocks developed in felsic volcanic or volcanogenic sedimentary rocks of the Isle Galet Formation (Colman-Sadd, 1976, 1980). Near Barasway de Cerf the same formation contains a trilobite pygidium of possibly Late Cambrian or Early Ordovician age (Colman-Sadd, 1976). A fossil locality on nearby Conne River contains trilobites of Early to Middle Ordovician (Floian to Dapingian) age (S. Colman-Sadd, pers. comm.). Boudinage of veins indicate a strong oblique down-dip stretching lineation. Structural investigations of this fault zone along strike along the shores of Baie d'Espoir show juxtaposition of moderately NW-dipping dark greenschist facies phyllite and phyllonitic felsic volcanic rocks of the Isle Galet Formation with mylonitic schists of the Little Passage gneiss (see Stop 1.6 below). The shear zone-related mylonitic foliation contains intrafolial isoclines of quartz veins, which in turn are overprinted by two generation of mesoscopic folding. "Chocolate-tablet boudinage" seen in veins suggests the fault accommodated a high flattening strain. Shear-sense indicators are ambiguous, but are consistent with a reverse component. Not all of the features discussed above are readily visible in these roadcut outcrops, but the fault zone is marked by a prominent topographic depression (seen to the northwest) which links to the coastal outcrops; the metamorphic rocks of the Little Passage gneiss, to the south, show a marked topographic and vegetation contrast with the terrain underlain by the lower-grade sedimentary and volcanic rocks.

Stop 1.6: Pelitic schists and psammite of the Little Passage gneiss injected by muscovite-bearing leucocratic granite veins (UTM 605803E / 5298247N)

This stop is located a short distance south of the Day Cove fault, about 1.3 km from Stop 1.5. The rocks contrast strongly with all outcrops seen previously, and a previous description given by Colman-Sadd and O'Driscoll (1978) is augmented below.

The rocks are paragneisses and schists consisting of quartz, mica and feldspar, and contain variable amounts of garnet, staurolite and sillimanite, and also tourmaline and pyrite. Complex folding is obvious, and no primary sedimentary structures are reported. These pelitic schists interlayered with thin bedded psammite were folded into SE-overturned F_2 folds, which are accompanied by a fanning S_2 crenulation cleavage of S_1. S_1 is axial planar to intrafolial F_1 folds in the psammite. The leucocratic granite veins likely belong to the Early Devonian North Bay granite suite, which contains rocks of similar aspect (Colman-Sadd, 1976; Dickson, 1990) and occur in two orientations: one set is roughly parallel to S_2 and weakly foliated; the other set is roughly parallel to S_1 and was folded, albeit less strongly than the host, and contains a well-developed S_2 fabric. Apparently the veins intruded in several orientations, and those with an orientation in the shortening field of the strain ellipsoid were folded and well-cleaved, whereas those that intruded in the extensional field were not, but developed a weak cleavage and were instead boudinaged. These relationships suggest that intrusion took place during F2, consistent with other lines of evidence that F2 is related to the Acadian orogeny, assuming that the early Devonian age inferred for the granite veins is correct. There is presently no direct geochronological information on the granitoid veins, but this would obviously be important information.

Stop 1.7: Northeastern extremity of the Gaultois Granite (here of dioritic composition) (UTM coordinates unavailable)

From Stop 1.6, continue approximately 2.2 km south on Route 360. These outcrops were previously described by Colman-Sadd and O'Driscoll (1978); this material is augmented below. The outcrops consist of foliated, melanocratic diorite. Although these outcrops are not typical of the Gaultois Granite as a whole, mapping indicates that this unit is continuous with, and grades into, more typical megacrystic granitoid rocks to the southwest. The diorite is cut by veins of leucogranite containing minor garnet and tourmaline, which are equated with the rocks at Stop 1.7 below (S. Colman-Sadd, pers. comm.)

Stop 1.8: Northwest Brook Complex granite close to Hermitage Bay fault (UTM 607663E / 5284389N)

From Stop 1.7, continue approximately 8 km south to prominent outcrops located in roadcuts and gravel pits on the right (west) side of Highway 360. These outcrops were previously described by Colman-Sadd and O'Driscoll (1978); this material is augmented below.

The red K-feldspar porphyritic muscovite-biotite granite, locally containing minor garnet, is dissected by numerous brittle faults and joints. Locally it also contains a weak shear fabric with structures suggesting dextral strike-slip movement. The shear fabric formed under greenschist facies or lower conditions, as feldspar shows no recrystallization. Cross-cutting pegmatite zones in these outcrops contain garnet and tourmaline.

Stop 1.9: Hermitage Bay fault in Northwest Brook granite (UTM 607206E / 5283492N)

From Stop 1.8, continue southward on Route 360 to the Junction for Route 362. The road descends into the deep valley that marks the trace of the Hermitage Bay fault. Turn left on Route 362, and shortly afterwards, turn left into large gravel pits located in the bottom of the valley.

In these outcrops, K-feldspar porpyritic granite akin to that observed at Stop 1.6 is chloritized and deformed into a subvertical cataclasite and associated minor ductile-brittle shears. Lineation is shallowly plunging and indicates the fault here accommodated mainly strike-slip movements. No reliable shear-sense indicators have been observed.

Stop 1.10: Sheared mafic volcanic rocks of Avalonian affinity on the other side of the Hermitage Bay fault (UTM coordinates unavailable)

From Stop 1.9, return to Route 362, and drive westward to the first prominent set of roadcut outcrops. We have now crossed into Avalonia. The original rock type for these outcrops is not easily resolved due to their extensive brittle deformation overprint, but the dark colour and abundance of chlorite and epidote strongly suggests a mafic volcanic protolith, and they are assigned to the Doughball Point Formation (part of the Connaigre Bay Group) of O'Brien (1998).

This is the last Stop for Day One; from here we return to Baie D'Espoir.

Day Two: Paleozoic Evolution of the Avalonian Rocks of Northern Fortune Bay and the Connaigre Peninsula

The Day Two field stops are all located in the area between Highway 360 and the communities of Pool's Cove, Belleoram, English Harbour West and Wreck Cove (Figure 8). Some adjustment of stop order may be needed for time-management purposes.

Stop 2.1: Simmons Brook Intrusive Suite and possible Devonian granite dykes (UTM 610000E / 5279700N)

From Baie d'Espoir, proceed along Route 361 to Route 360, and drive southward past previous from Day One, and then turn left on Route 362, passing Stop 1.9 from Day One. Follow Route 362 (signed for Pool's Cove and Belleoram) for a distance of 6 km from its junction with Route 360, and turn right (south) on to a gravel road that leads to a nearby communication tower. The road may be rough and difficulty to turn on, but the outcrops can easily be accessed on foot from the junction with Route 362.

The Simmons Brook Intrusive Suite consists of hornblende ± biotite bearing granodiorite to quartz-diorite quartz with lesser amounts of granite and gabbro. These rocks extend from Harbour Breton in the southwest to East Bay in the northeast, forming a 5- to 10-km wide band bounded by the East Bay-White Horse fault in the south and the Hermitage Bay in the North. In the East, the Simmons Brook Suite is unconformably overlain by the Pools Cove Formation (Stop 2-3), and in that locality it has been dated at 621 ± 3 Ma (O'Brien et al., 1995). It is intruded by K-feldspar porphyritic hornblende granite, grouped with the Harbour Breton Granite, which yielded a preliminary U-Pb zircon age of ca. 575 Ma (Kellett et al., in press). The outcrops in the road show the typical homogeneous and hornblende-rich character of this unit, and also contain dykes of pink felsic granite to porphyry, which clearly intrude the granodiorite. Visually, these rocks resemble some variants of the "Old Woman Stock", a Devonian granite to be visited later in the day, and they are thought to be of the same age. However, given the lack of direct age data and the presence of several generations of granitoid rocks in this part of Avalonia, other interpretations cannot be ruled out.

The Simmons Brook Intrusive Suite has an unusually evolved Nd isotope signature (εNd of -6.3 to -8.2 at 600 Ma) compared to other intrusive rocks across Avalonia in Newfoundland, which almost all have "juvenile" Nd isotopic signatures (εNd of +1 to +6) . This result suggests an older crustal component in the area of northern Fortune Bay that is not reflected amongst intrusive rocks of equivalent age to the east (Kerr et al., 1995). More data are required to confirm and possibly extend this pattern, and to assess its significance in the light of other new results, such as the Silurian age for the Pass Island Granite (Kellett et al., in press; see earlier discussion).

Stop 2.2: Devonian dykes intruding the Pool's Cove Formation (UTM 612612E / 5279208N)

From Stop 2.1, return to Route 362, and continue east to the junction where the road to Pool's Cove diverges, a distance of about 1.5 km. Take the road towards Pool's Cove for approximately 200m and stop at the outcrops on the right hand side of the road.

This location introduces the terrestrial sedimentary rocks of the Pool's Cove Formation. The red conglomerate is intruded by several porphyritic felsic dykes, which are probably offshoots of the ca. 376 Ma Old Woman Stock granite pluton (see stop 2.11 below). The dykes have prominent contact metamorphic aureoles, despite their narrow widths. The extent of the metamorphic aureole suggests that the intrusion of the Middle Devonian dykes took place whilst the conglomerate was still wet, and that the water contained in the sediments acted as a heat carrier. If the correlation with the Old Woman stock is correct, the Pool's Cove Formation is late Early to Middle Devonian. Closely similar dykes are also found along the coast of the Cinq Isles, consistent with their correlation with the nearby Old Woman Stock pluton.

Stop 2.3: Basal unconformity of the Pool's Cove Formation (UTM 613350E / 5279800N)

From Stop 2.2, continue 1.5 km east towards Pool's Cove, and examine outcrops exposed in Simmons Brook to the left (north) of the road; a short access trail is located just before the bridge. This locality is also described in the Traveller's Guide to the Geology of Newfoundland and Labrador (Colman-Sadd and Scott, 1994).

The outcrop about 30 m upstream shows the near-vertical unconformity at the base of the Lower to Middle Devonian Pool's Cove Formation, which here is in contact with granitoid rocks of the Simmons Brook Intrusive Suite. The granitoid rocks are cut by narrow diabase dykes, and pebbles of the older unit are included within the basal layers of the younger sedimentary unit. In other locations similar conglomerate is in tectonic contact with older rocks, or lies disconformably (Greene and O'Driscoll, 1976; Williams and O'Brien, 1995) upon the Cinq Isles Formation, which hence is older and probably Lower Devonian. The Cinq Isles Formation appears to have been subjected to more intense deformation, including cleavage formation, consistent with the presence of an unconformity within the Devonian sedimentary sequence (see stop 2-10 for further discussion)

Stop 2.4: Pool's Cove Formation – conglomerates with plutonic boulders (UTM 617950E / 5281350N)

From Stop 2.3, continue towards Pool's Cove, and stop by the fish warehouse facility close to the end of the road.

In this location, the Pool's Cove Formation consists of boulder conglomerates, with strata dipping at about 30^{o} to the southwest; aside from the tilting, deformation is absent. The boulders are mainly of plutonic composition and derived from the adjacent Neoproterozoic intrusive suites that were being eroded at that time. Elsewhere, the conglomerate also contains sedimentary, metamorphic, and volcanic cobbles, and also quartz clasts probably derived from vein materials. The deformation of the Pools Cove Formation is very heterogeneous and its attitude varies from nearly horizontal to moderately- or steeply-dipping, due to upright folding. Foliations are locally developed, and deformation seems to increase in intensity adjacent to faults.

Stop 2.5: Deformed (folded) rocks of the Chapel Island Formation (UTM 611825E / 5272300N)

From Stop 2.4, return from Pool’s Cove to the junction at Stop 2.2 (about 9 km), and continue on the road towards Belleoram for approximately 5 km. Outcrops on both sides of the road show rusty weathering.

The sedimentary rocks mapped as part of late Ediacaran to Early Cambrian Chapel Island Formation by O’Brien et al. (1995). These sedimentary rocks conformably overlie shallow marine sediments assigned to the Rencontre Formation. Sedimentation was essentially continuous across the Precambrian-Cambrian boundary, as seen also on the southern part of the Burin Peninsula, across Fortune Bay. This outcrop comprises sandstones, siltstones and dark shales, which are complexly folded and locally cleaved (Plate 1). Along the coast, folding in this unit is associated with small thrust zones, and the development of broken formations (are these tectonic melanges?). The intensity of deformation in these older rocks is generally more intense and complex compared to the heterogeneous and localized deformation observed in the Cinq Isles and Pool’s Cove formations. The outcrop suggests that the Chapel Island Formation was subjected to a complex deformation involving folding and faulting, both of which are inferred to have occurred during the Early Devonian Acadian orogeny. The polarity and asymmetry of folds in these outcrops suggests that they are southeast-verging.

Stop 2.6: Unconformity beneath the Great Bay de l’Eau Formation (UTM 613600E / 5257650N)

From Stop 2.5, continue south for 15 km on Route 362, and then turn right at the intersection. Continue on Route 363 for 5 km, and then turn left at the junction for English Harbour West. After about 0.9 km, turn left again at the Stop sign, and continue for another 0.5 km. Note that we may decide to visit Stop 2.7 (Belleoram Granite) before 2.6 for logistical reasons.

These outcrops show moderately to steeply south-dipping white quartzite assigned to the Cambrian Random Formation, which conformably overlies clastic sedimentary rocks assigned to the Chapel Island Formation. The Random quartzite in turn is overlain by red and green shale, mudstone and minor sandstone assigned to the Chamberlains Brook Formation. The Ediacaran to Cambrian succession is unconformably overlain by the gently south-dipping Great Bay de l’Eau Formation (visible from the other side of the bay), which in turn is intruded by the Middle to Late Devonian (?) Belleoram granite (O’Brien, 1998; see Plate 2). The relationships suggest that the Great Bay de l’Eau Formation is probably Middle to Upper Devonian in age, and probably was deposited during the last stages of the Acadian orogenic episode; the angular unconformity is inferred to mark the uplift and exhumation of Avalonia following the deformation induced during the main phase of the Acadian Orogeny.

Stop 2.7: Belleoram Granite (UTM 619741E / 5262802N)

From Stop 2.6, return to Route 363, and drive back to the intersection with Route 362, then turn right for Belleoram. Continue on this road for about 6 km to roadside outcrops located high on a hillside above the water, with spectacular views across to Chapel Island. Note that we may visit this stop before those of the English Harbour West area if time and logistics permit.

These outcrops are typical of the Belleoram Granite. In clear weather, the view across to Chapel Island reveals a cross-section through the roof zone of the granite, and granitic and composite mafic-felsic dykes cutting country rocks of the Chapel Island Formation.

The Belleoram Granite represents one of two Devonian granitoid intrusions in the area; the other is represented by the Middle Devonian (ca. 376 Ma) Old Woman Stock (see Stop 2-11). The two Devonian intrusions comprise equigranular grey to pink, quartz monzonite to granodiorite, and red feldspaphyric microgranite (O'Brien et al., 1995). The Belleoram Granite is presently undated (work is in progress) but its age is constrained by the fact that it intrudes both the Chapel Island and Pool's Cove formations. The Belleoram Granite is characterized by the widespread presence of rounded, fine-grained mafic enclaves. By comparison with similar features described from many other granite plutons, such as the Fogo Island Intrusion, these are interpreted as frozen globules of coexisting mafic or hybrid magmas (e.g., Kerr, 2013). Nd isotope investigations of these inclusions and their host granites (Morrissey, 1993; Kerr et al., 1995) show that they have the same signatures (εNd of around +2) indicating that the mafic and felsic magmas either had similar sources or that inclusions were isotopically homogenized with surrounding magma.

Stop 2.8: Porphyritic phase of the Belleoram Granite (UTM 615750E / 5260650N)

From Stop 2.7, a short scenic excursion towards Belleoram may be possible; the views of this picturesque community and the surrounding steep mountains are spectacular. On the return trip towards Route 363, about 6 km from Stop 2.7, a small quarry is located on the left (east) of the road. This is an optional stop that reveals a high-level porphyritic variant of the Belleoram Granite. Note that we may elect to miss this stop for logistical reasons, or possibly visit briefly on the return trip from Wreck Cove (see below).

Stop 2.9: The Boxey Trail Section (UTM 609651E / 5255863N)

From Stop 2.8, return to Route 363, and continue southwest for about 10 km, to the signpost for the "Boxey Trail", which diverges to the left to access the shore along a small peninsula. The Stop contains two parts, accessed by a short hike.

The first outcrop (UTM 609651E / 5255863N) shows gently-dipping red conglomerates of the Great Bay de l'Eau Formation, which here dip gently to the southeast. Continue along the trail to the shore of the headland (UTM 609639E / 5255198N). Outcrops along the cliffs show complex intrusive relationships, where granitic dykes intrude the conglomerate. There are also basaltic units here, which are interpreted as sills; these are probably equivalent to basaltic volcanics that occur within higher parts of the Great Bay de l'Eau Formation (Williams, 1971; O'Brien, 1998). The granitic rocks are undated, but equated with the Belleoram Granite; the mafic sills and flows also remain undated.

Stop 2.10: Acadian folding and thrusting of the Cinq Isles Formation at Wreck Cove (UTM 604600E / 5261100N)

From Stop 2.9, return to Route 363, and continue south for 5.5 km, and then turn right on the road to Wreck Cove. Drive for 4.5 km, then turn left just before Cox's Grocery Store, and park by the wharf to walk along the shore. Gently-dipping sedimentary rocks of the Cinq Isles Formation, the oldest Devonian sedimentary unit in the area, are here affected by a variety of structural complications.

The Cinq Isles Formation is the oldest unit incorporating Devonian terrestrial and/or shallow marine sedimentary rocks ("Old Red Sandstone") in the northern Fortune Bay area. It comprises red micaceous sandstone, quartz-pebble conglomerate, red mudstone and red and grey limestone. The latter forms a distinctive part of this unit. The Cinq Isles Formation unconformably overlies the Simmons Brook intrusive suite west of Pool"s Cove. It is commonly more intensely and complexly deformed than the overlying Middle-Upper (?) Devonian red beds, suggestive of an important Early-Middle Devonian (Acadian) unconformity within the Devonian sequence. The Cinq Isles Formation is interpreted as a foredeep molasse sequence that was deposited at a relatively early stage of the Acadian orogeny, as a result of the progressive tectonic loading of Avalonia by Ganderian rocks.

Stop 2.11: Mineralization and alteration in the granite of the Old Woman Stock (UTM coordinates unavailable)

This stop is located 12.5 km north of the Route 362/Route 363 intersection, within a large area of quarries and gravel pits located on the right (east) side of Route 362. The outcrops consist of variably altered and bleached granite and quartz-feldspar porphyry, with localized fresh areas where original textures are well-preserved. The alteration includes abundant sericite, and is suspected to also include clay-mineral alteration such as kaolinite and dickite. Alteration of this type is typical of high-level mineralized granites. Mineralization is sporadic at this locality, and consists of disseminated splashes of molybdenite and patches of interstitial fluorite; there is also widespread very-fine-grained pyrite in many areas. A larger molybdenite showing including both disseminated and vein-hosted molybdenite mineralization (Leonard's Find) is located less than 1 km to the southwest, and several other molybdenite and fluorite indications are noted in the area.

The Old Woman Stock was originally included with the Harbour Breton Granite, but was recognized as a discrete younger unit by O'Brien (1998). The presence of narrow granite veinlets in the adjacent Pool's Cove conglomerate in the northern part of the intrusion (O'Brien et al., 1995) and the presence of probable consanguineous porphyritic dikes at Stop 2.2 suggest that the pluton might extend much further to the northeast at depth. Kellet et al. (in press) report a U-Pb zircon age of 376 ± 3 Ma for the Old Woman Stock, which provides a younger age constraint for the Pool's Cove Formation. Lynch et al. (2012) report a slightly older Re-Os molybdenite age of ca. 382 Ma for the nearby Leonard's Find showing.

This is the final stop for Day Two. From here, return to Route 360 and to Baie d'Espoir.

Day Three: Some Miscellaneous Outcrops along Route 360.

The Stops for Day Three are of general interest, and two have connections to economic geology and mineral potential. Other Stops are of general geological interest for students. Locations for these stops are shown in Figure 7.

Stop 3.1: Tungsten-bearing skarns and granite veins, Great Gull Lake area (UTM 612910E / 5547810N)

From Baie d'Espoir, return to Route 360, and turn north towards Bishops Falls and the Trans-Canada Highway. Drive northward for approximately 38 km, to a series of quarry pits located on the right (east) side of the road. If coming in the opposite direction, the location is about 2.3 km south of a gravel access road to a communication tower, which branches off to the east about 8 km south of where Route 360 passes the shores of Little Gull Lake, These outcrops may be partially flooded and not fully accessible in all areas; participants should take care around steep slopes located above flooded areas. A general description of these outcrops is given in the Traveller's Guide to the Geology of Newfoundland and Labrador (Colman-Sadd and Scott, 1994); this is augmented below.

These outcrops are located in metasedimentary rocks of the Baie d'Espoir Group, which probably form part of the North Steady Pond Formation, dominated by grey-green shale, slate and sandstone, locally calcareous, and rusty-weathering due to disseminated pyrite. Bedding in the sedimentary rocks here dips gently to moderately southwest, but in some areas appears steep, suggesting that folds are present. These sedimentary host rocks are partially replaced by massive white material dominated by carbonates and calc-silicates; these zones are quite striking and have a gneiss-like appearance in some areas, presumably because relict bedding is preserved as dark streaks. The replacement zones contain disseminated pyrrhotite bands, and also a pale green mineral that resembles malachite (but may not be). Locally, they contain clinopyroxene, garnet and the tungsten-bearing mineral scheelite ($CaWO_4$). Scheelite is difficult to identify on the basis of appearance, and is commonly present in small amounts; its best diagnostic property is blue fluorescence under short-wave UV light, which we will not be able to demonstrate. The outcrop is cut by numerous veins of texturally variable muscovite-bearing granite, pegmatite and aplite, and surrounding outcrops also contain numerous quartz veins. Some of the quartz veins are also reported to contain scheelite, and one loose sample of vein material examined by AK in 2009 contained a black mineral thought to be the similar mineral wolframite ($(Fe,Mn)WO_4$). No detailed mineralogical, petrological or geochemical work has ever been conducted on these occurrences, but they would make an excellent undergraduate thesis topic for the right individual.

These zones are believed to be skarns, developed through the interaction of hydrothermal fluids from nearby granitoid intrusions with calcareous and pyritiferous rocks of the Baie d'Espoir Group. They have been explored on a limited scale (see Kerr et al., 2009, for a review and references), but both channel sampling and three reconnaissance drill holes yielded only sporadic low-grade material, forming multiple narrow zones (typically a few cm thick) containing < 1% WO_4. The best intersection was 0.2 m of 2.7% WO_4. The drill core has not been examined or sampled, but descriptions suggest that scheelite is not always present in altered material. The granite and pegmatite veins that are common in these outcrops are interpreted to indicate the presence of an underlying intrusion, perhaps part of the Middle Ridge Granite, an extensive leucogranite body that has given an early Devonian U-Pb monazite age (410 ± 3 Ma; R. Tucker, quoted by Kerr (1997). The mineralization known in this area likely has no economic potential, but it represents the only skarn-type granophile mineralization yet reported in Newfoundland; the surrounding areas may have potential for further exploration, given interest in tungsten as a commodity.

Stop 3.2: Chromite and Magnesite in the Great Bend Ophiolite (UTM coordinates unavailable)

From Stop 3.1, continue 52 km northward, to the area of the Great Bend ophiolite (also visited on Day One). This stop is located a short distance (0.8 km) south of the large quarry visited at Stop 1.1, close to an open area located on the right (east) side of the road. An abandoned road leads to a smaller quarry, a few hundred metres from the road. It is described by Colman-Sadd and Swinden (1983) and Colman-Sadd and Scott (1994). The ultramafic rocks in this area lie close to the transition into gabbroic rocks exposed to the south, and have been pervasively altered to magnesite ($MgCO_3$), which is associated with white quartz. The magnesite weathers brown, but is white on fresh surfaces. Magnesite-rich zones occur in other Newfoundland ophiolites at approximately the same stratigraphic level, between the ultramafic rocks and overlying gabbroic material. The outcrops also contain chromite pods, which appear to have resisted the alteration that generated the magnesite. This area has been investigated for its potential as a magnesium source, but appears to be too small as presently defined. Information on previous work is contained in MODS file 002D/11/Mg008 and Kean (1974).

Stop 3.3: Sedimentary structures in the Botwood Group (UTM coordinates unavailable)

From Stop 3.2, continue 61.7 km north on Route 360, back into rocks of the Dunnage Zone (Exploits Subzone). These roadside outcrops are red and green sandstones of the Silurian Botwood Group. They display well-developed ripple marks and locally have bedding surfaces that display mud cracks suggesting periodic desiccation. The description is taken from Colman-Sadd and Swinden (1983). From Bishop’s Falls, the field trip returns to Gander and St. John’s.

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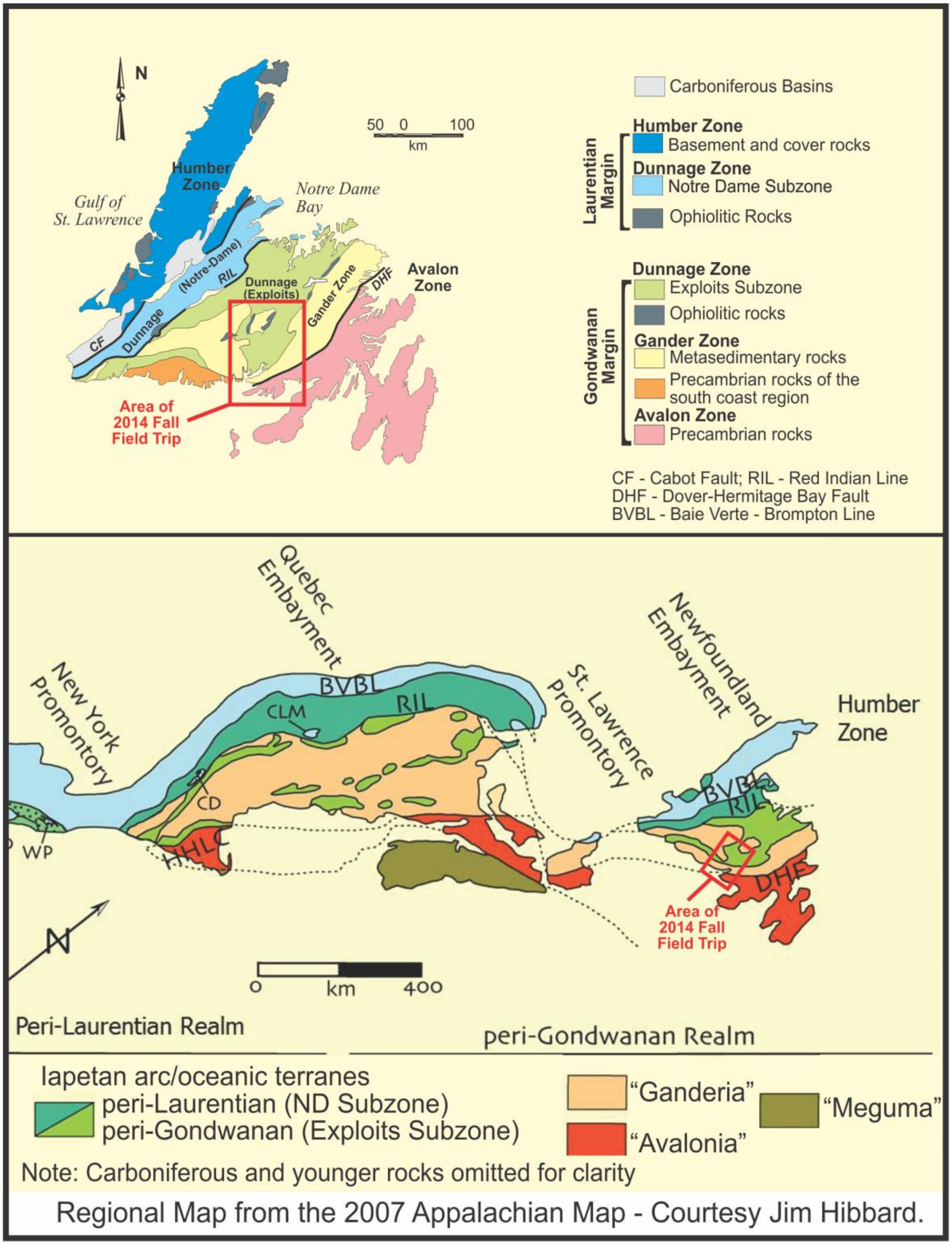

Figure 1. Subdivisions of the Appalachian Orogen in Newfoundland, Atlantic Canada and the adjacent USA, showing the context of the field trip area.

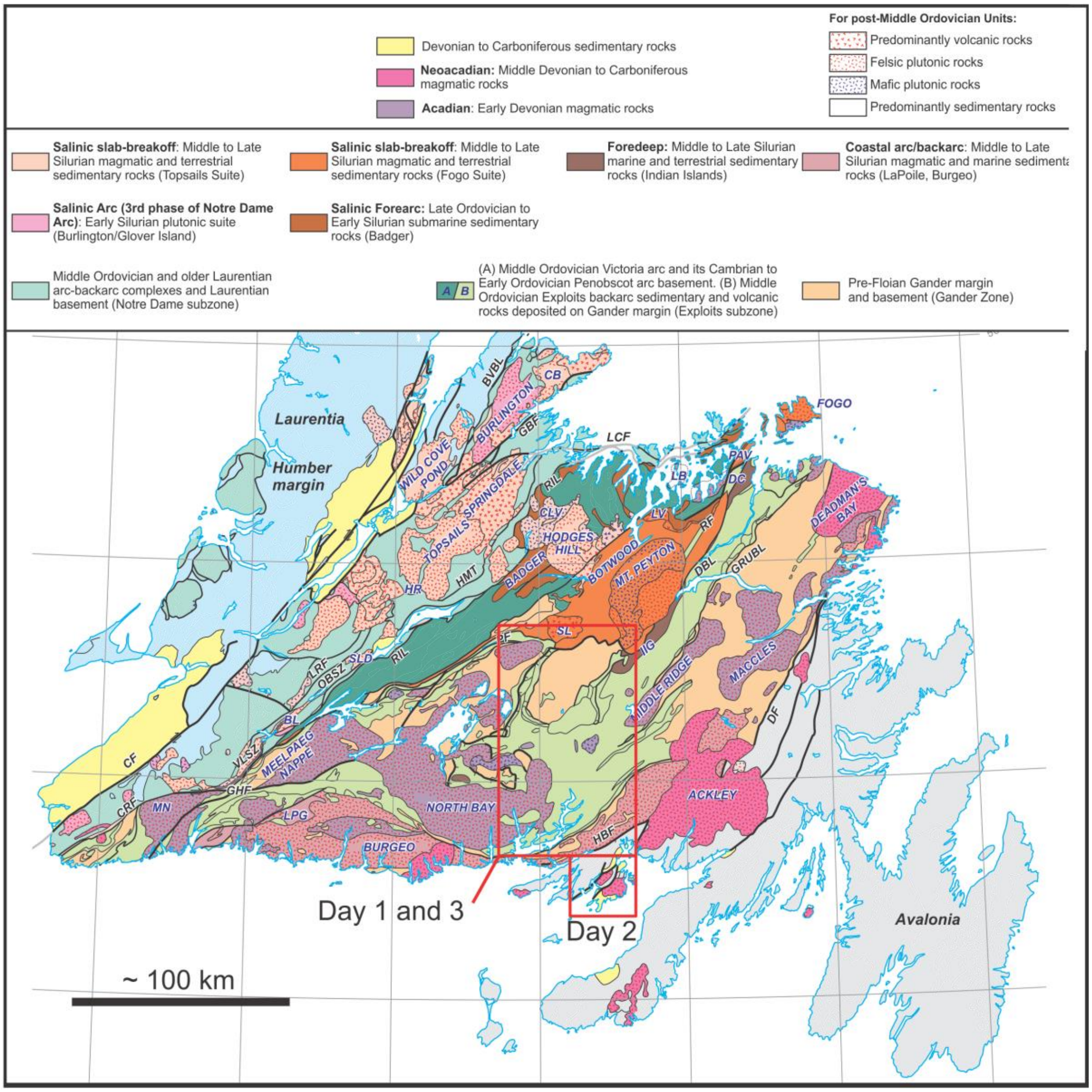

Figure 2. Thematic map of the geology of Newfoundland (modified from Hibbard et al., 2006), showing the area of this field trip. BL Boogie Lake pluton, BVBL- Baie Verte-Brompton Line, CB Cape Brule porphyry, CF Cabot Fault, CLV Charles Lake volcanics, CRF Cape Ray Fault, DBL Dog Bay Line, DC Duder Complex, DF Dover Fault, GHF Gunflap Hills Fault, GRB Green Bay Fault, GRUBL Gander River Ultrabasic Belt Line, HBF Hermitage Bay Fault, HMT Hungry Mountain Thrust, HR Harry's River, IIG Indian Islands Group, LB Loon Bay pluton, LCF Lobster Cove Fault, LPG La Poile Group, LRF Lloyds River Fault, LV Laurenceton volcanic, MN Meelpaeg Nappe, OBSZ Otter Brook shear zone, PAV Port Albert volcanic, PF Pine Falls Formation, RF Reach Fault, SL Stony Lake volcanics, RIL Red Indian Line, SLD Star Lake Dam, VLSZ Victoria Lake Shear Zone. NOTE: not all of the above features are referenced in the text of this field guide.

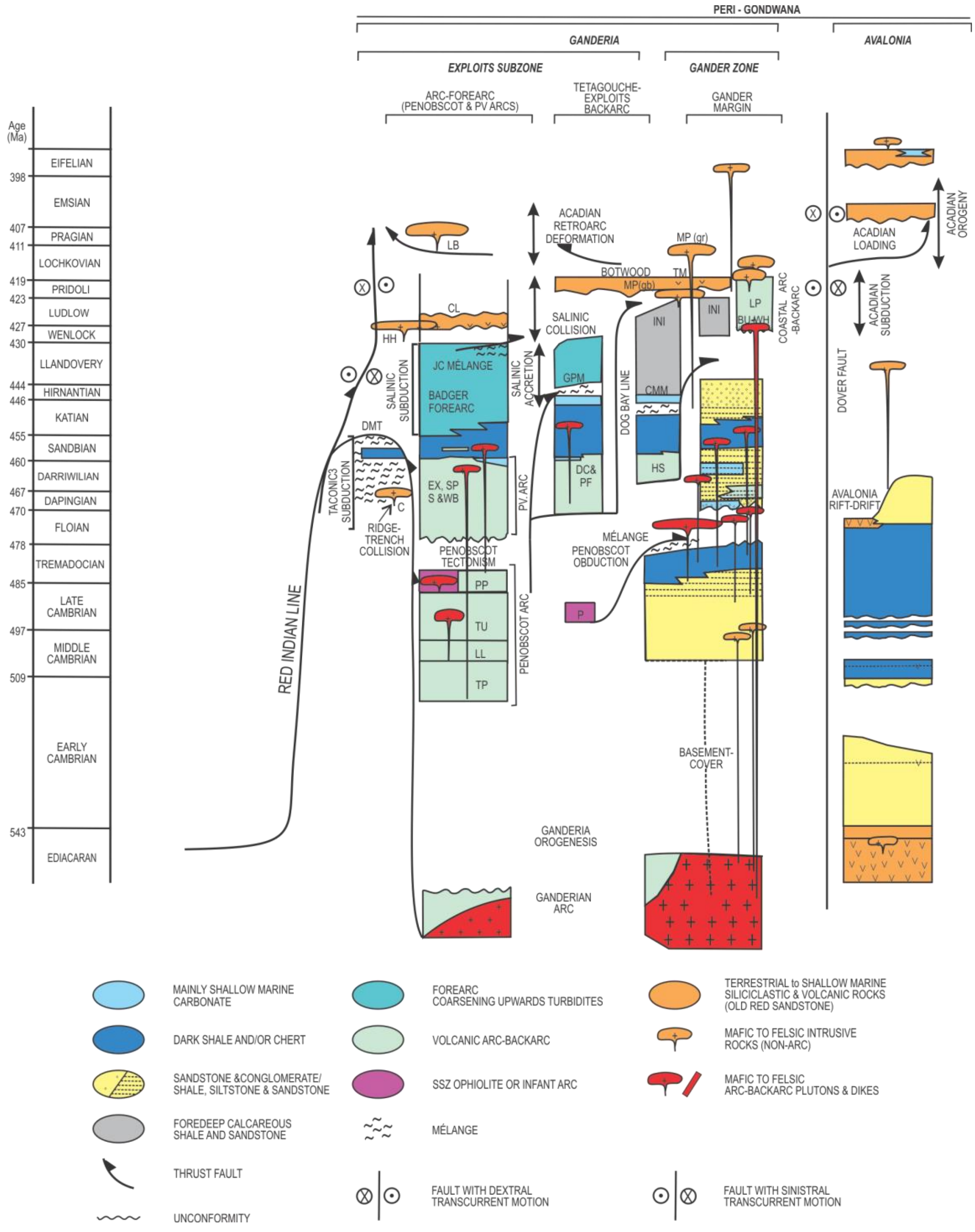

Figure 3. Tectono-stratigraphic columns and structural relationships of the various elements of Ganderia and Avalonia (modified from van Staal et al., 2014). The peri-Gondwanan terranes are bounded to the west by the Red Indian Line, which separates these from the peri-Laurentian terranes (not shown here). BU Burgeo Intrusive Suite; C Coaker Porphyry; CL Charles Lake volcanics; CMM Carmanville melange ; DC Duder Complex; EX Exploits Groups; GPM - Garden Point melange; HH Hodges Hill Complex; HS Hamitlon Sound Group ; INI Indian Islands Group; JC Joey's Cove; LB Loon Bay pluton; LL Long Lake Group; LP La Poile Group; MPgb gabbro phase of Mount Peyton pluton; MPgr late granite phase of Mount Peyton pluton ; P Pipestone Pond Complex; PF Pine Falls Formation; PP Pats Pond Group; PV Popelogan-Victoria; S Summerford Group; SP Sutherlands Pond group; TM Ten Mile Formation; TP Tally Pond Group, TU Tulks Group; WB Wild Bight Group; WH Western Head granite. NOTE: Not all of these features are referenced in the text of this field guide.

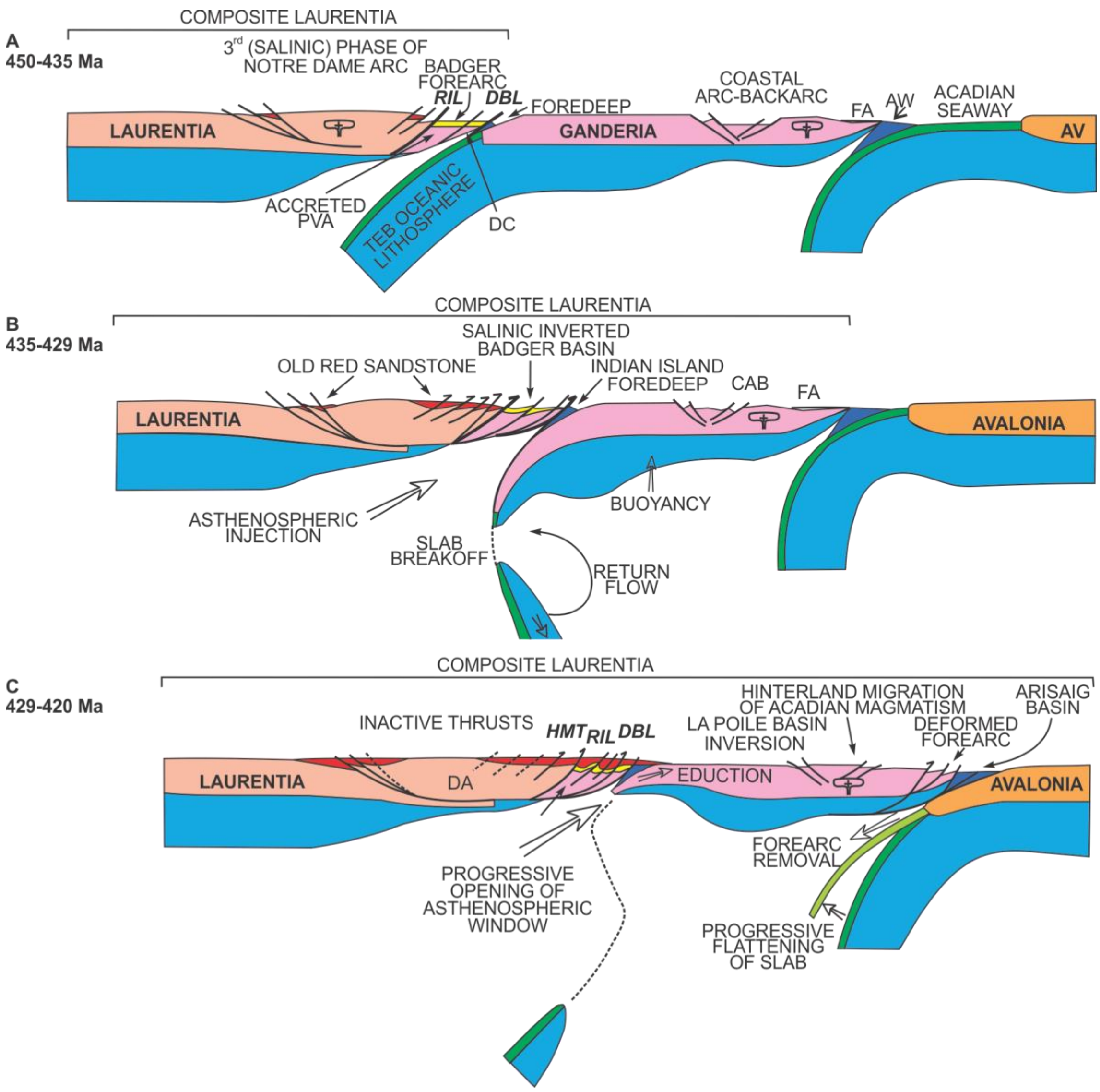

Figure 4. Tectonic model for Salinic and Acadian subduction and orogenesis (modified from van Staal et al., 2014).

(A) Late Ordovician-Early Silurian closure of the Tetagouche-Exploits backarc basin (TEB) and start of the Salinic collision of composite Laurentia with the leading edge of the Gander margin. Salinic collision was coeval with (and hence may have been the cause of) initiation of subduction in the Acadian seaway beneath the trailing edge of the Gander margin, forming the coastal arc-backarc system (CAB). Red bed molasse sedimentation (shown in red) was initiated in basins that formed during early Salinic thrusting and uplift in the hinterland of the orogeny. Marine sedimentation took place in the Badger forearc basin. A marine foredeep accumulated Badger-like clastic sedimentary rocks and sedimentary rocks of the younger Indian Islands Group on the leading edge of the Gander margin.

(B) Progressive steepening of the Gander margin slab during and/or following tearing (break-off) of the TEB oceanic slab.

(C) Subduction of the Gander margin and eastward expansion of an asthenospheric window beneath the Salinic orogeny. The Acadian collision (when the leading edge of Avalonia enters the trench) starts at ca. 420 Ma and Avalonia is subducted beneath composite Laurentia, which is now represented by the accreted Gander margin. Progressive flattening of the down-going slab following the start of collision produced a hinterland-migrating retro-arc deformation zone and terminated in expulsion of the mantle

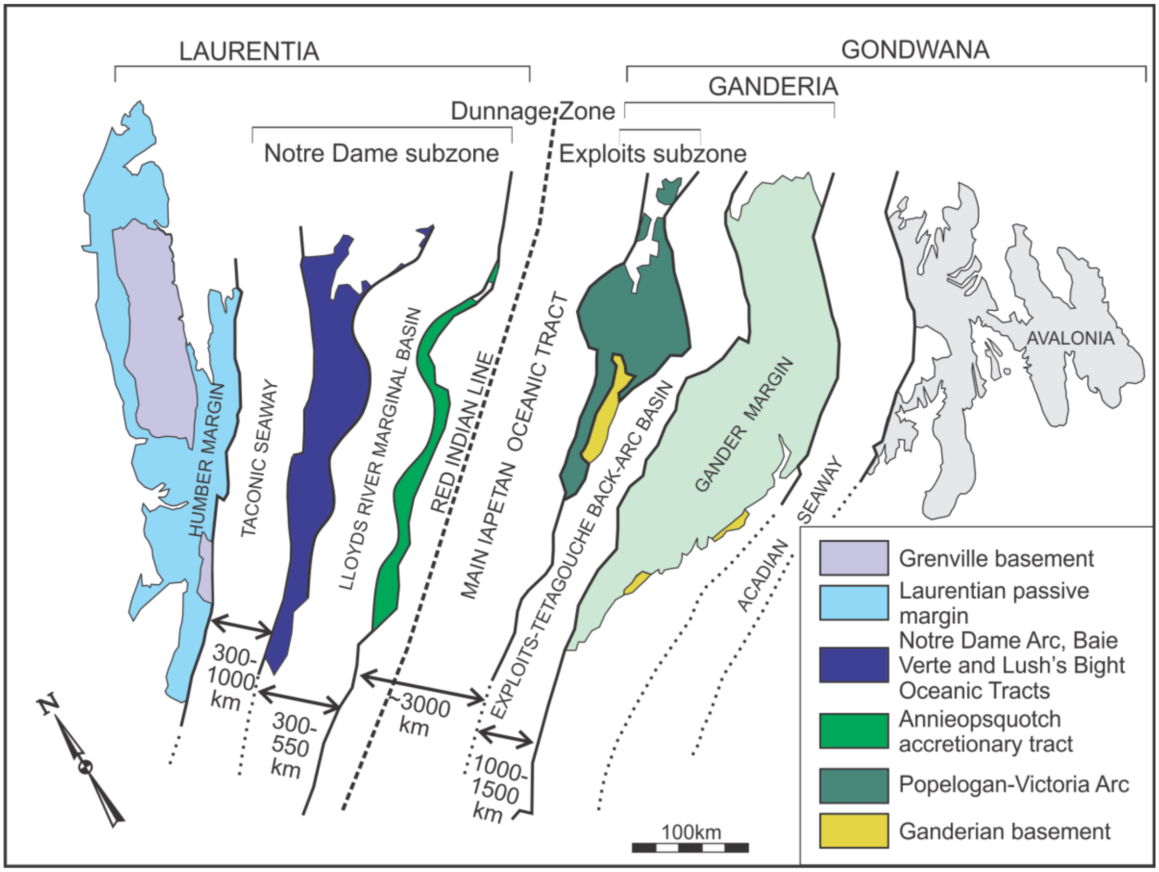

Figure 5. Tectonic elements of the Newfoundland Appalachians expanded to show seaways that occurred outboard of the Humber margin (modified from van Staal and Zagorevski, 2012). Closure of these seaways during the Cambrian-Devonian progressively expanded composite Laurentia (van Staal and Barr, 2014) towards the east and resulted in punctuated orogenic events (Taconic, Salinic and Acadian) in Newfoundland.

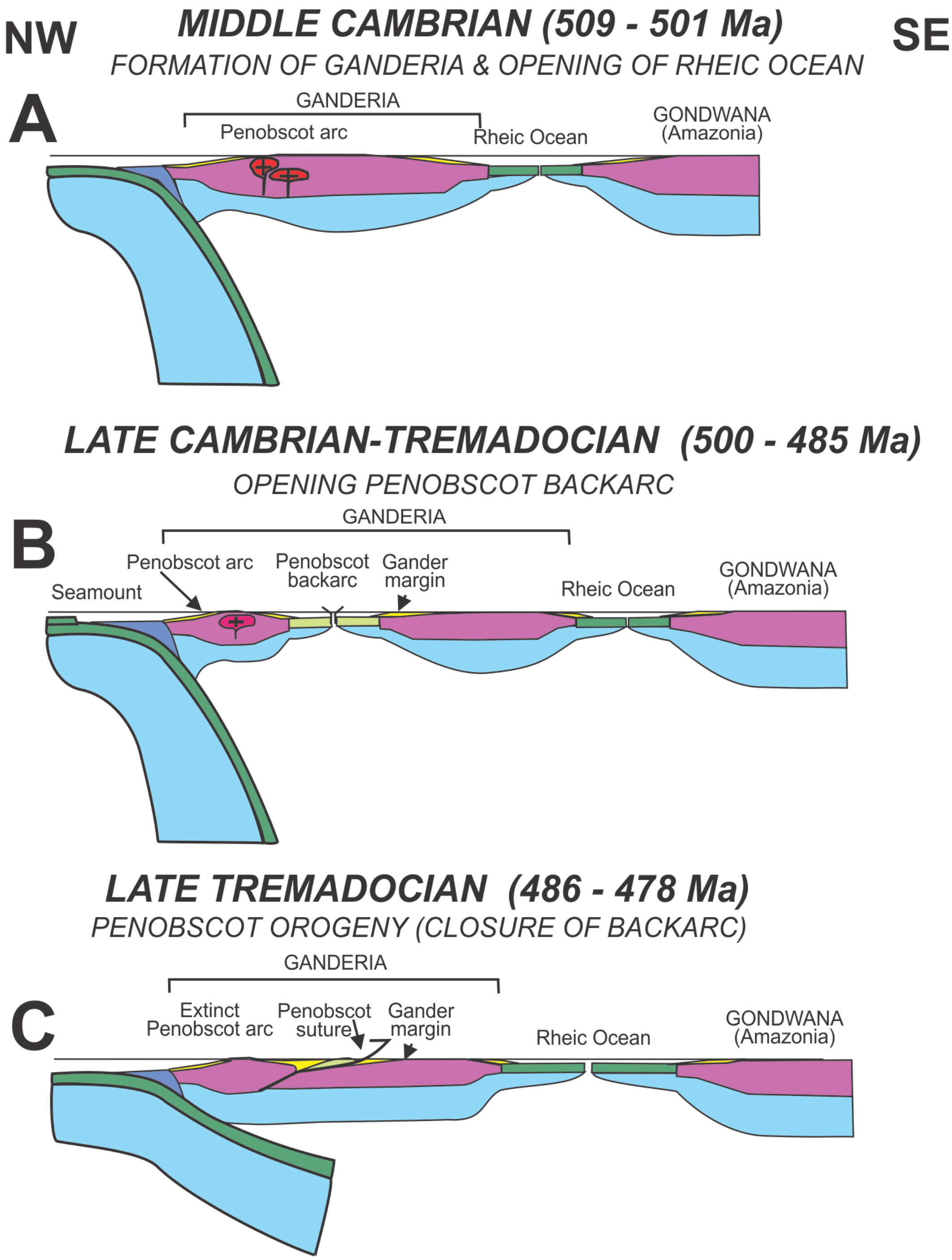

Figure 6. Cambrian-Early Ordovician tectonic evolution of Ganderia (after van Staal and Zagorevski, 2012). (A).Magmatic arc is built on Ganderia, concurrent with the development of the Rheic Ocean (van Staal et al., 2012); (B). rifting and drift of Ganderia further opening the Rheic Ocean, and the development of the Penobscot backarc basin within Ganderia; (C) Closure of the Penobscot backarc basin and obduction of ophiolites on to the Gander Margin.

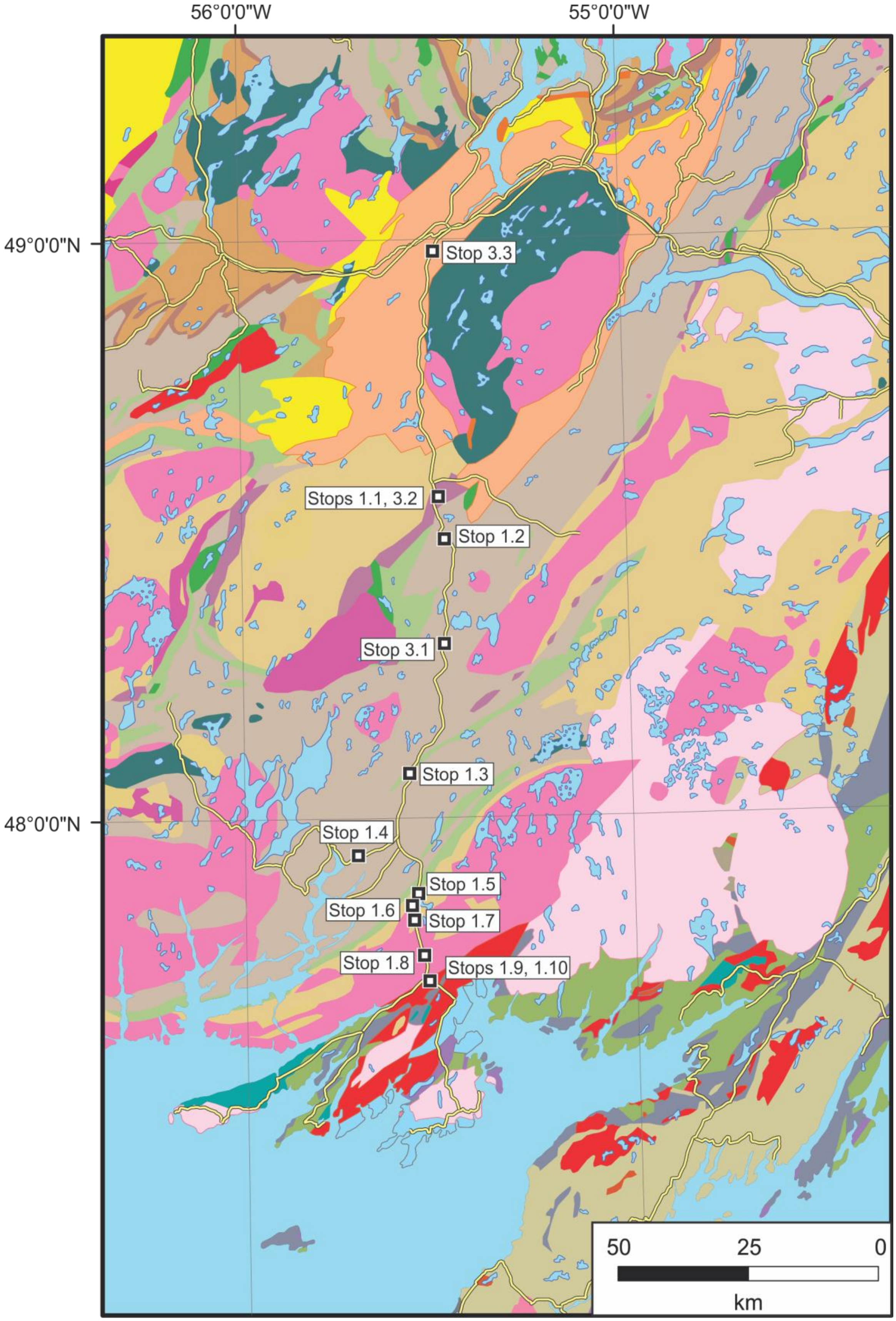
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Figure 7. Simplified geological map of the field trip area, derived from the 1:1 million scale map of Newfoundland, showing the approximate locations of field trip stops for Day 1 and Day 3. For the locations of field trip stops on Day 2, see Figure 8.

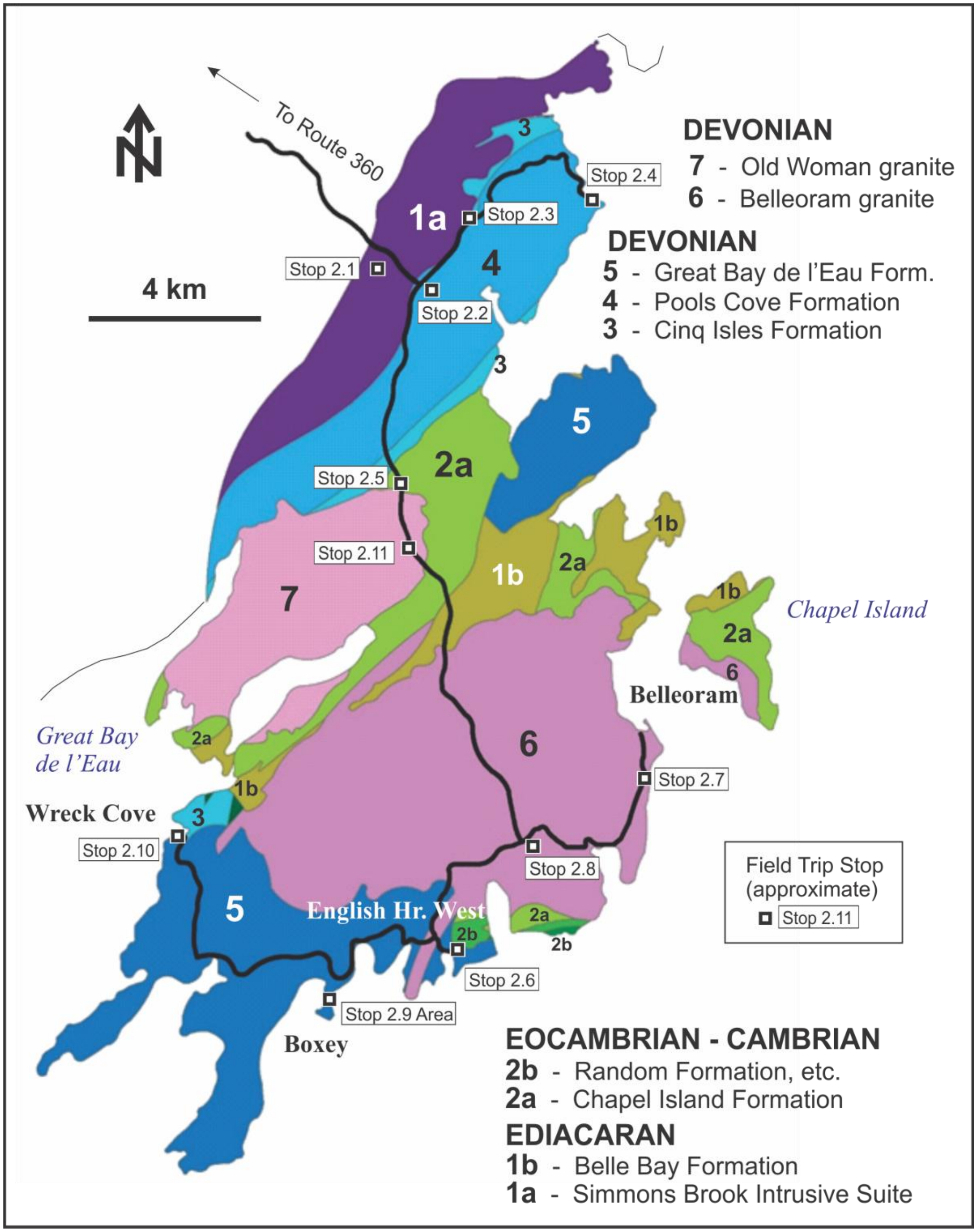

Figure 8. Field trip stops for Day 2. Geology after O'Brien (1998).

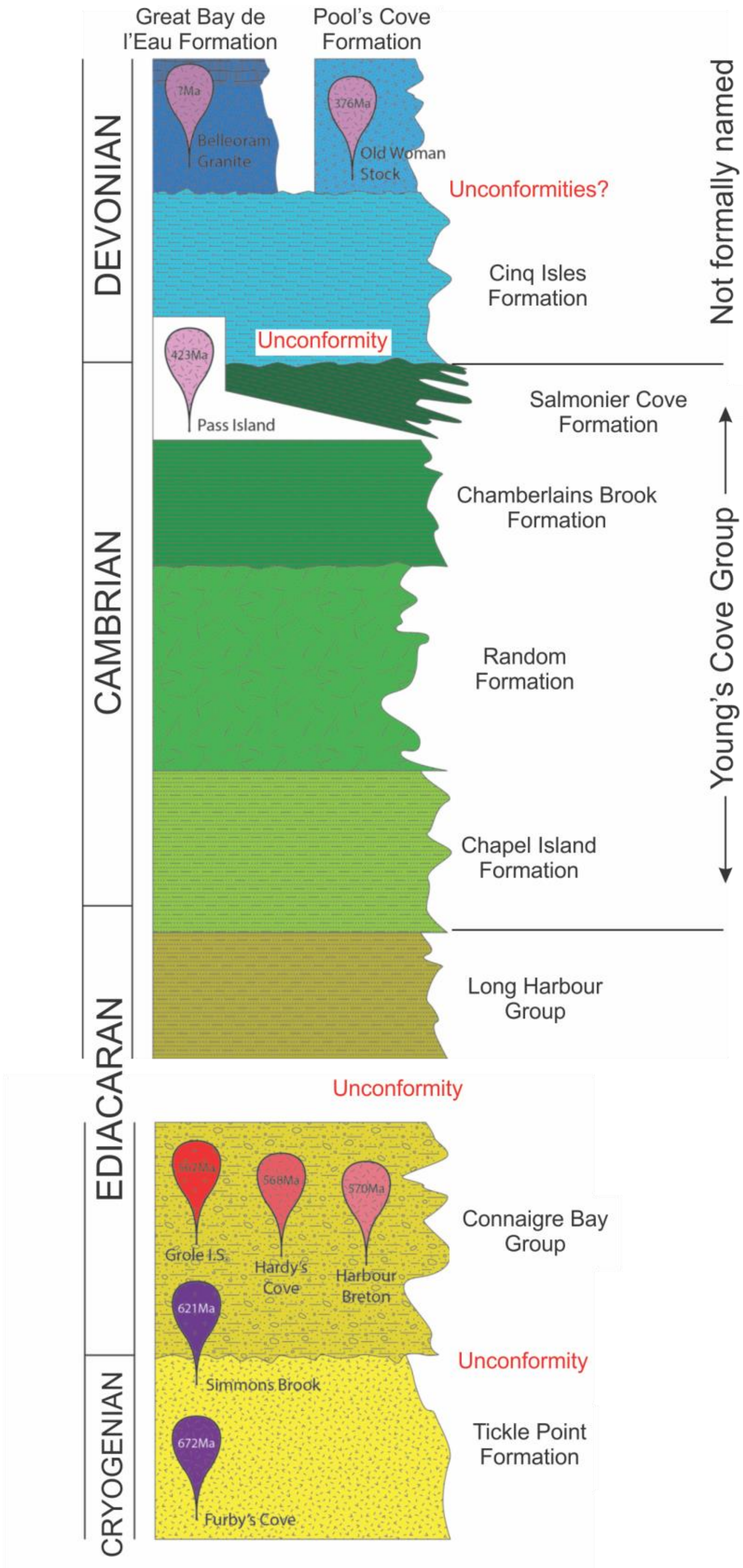

Figure 9. Generalized stratigraphic column for the area of northern Fortune Bay (partly after O'Brien et al, 1996; O'Brien, 1998).

Plate 1. F_1 and F_2 folding in rocks assigned to the Chapel Island Formation, along Route 361 (Stop 2.5).

Plate 2. Angular unconformity between Cambrian (Chapel Island and Chamberlain Brook formations) and Devonian sedimentary rocks of the Great Bay de l'Eau Formation at Blue Pinion Cove.

Era	Period	Epoch	DNAG Scale (1983)	354	Current Scale (2014)	359
PALEOZOIC	DEVONIAN	Upper	Famennian	364	Famennian	374.5
			Frasnian	370	Frasnian	385.3
		Middle	Givetian	381	Givetian	391.8
			Eifelian	391	Eifelian	397.5
		Lower	Emsian	400	Emsian	407
			Segennian	412	Pragian	411.2
			Geddinnian	417	Lochkovian	416
	SILURIAN	Upper	Pridoli	419	Pridoli	418.7
			Ludlovian	423	Ludfordian	421.3
					Gorstian	422.9
		Lower	Wenlockian	428	Homerian	426.2
					Sheinwoodian	428.2
			Llandoverian	443	Telychian	436.1
					Aeronian	439
					Rhuddanian	443.7
	ORDOVICIAN	Upper	Ashgillian	449	Hinantian	445.6
					Katian	455.8
			Caradocian)	458	Sandbian	460.9
		Middle	Llandeilian	464	Darriwillian	468.1
			Llanvirnian	470	Dapingian	471.8
		Lower	Arenigian	485	Floian	478.6
			Tremadocian	495	Tremadocian	488.3
	CAMBRIAN	Upper 505			(Stage 10)	~492
					(Stage 9)	~496
					Paioian	~499
		Middle 518			Guzhangian	~503
					Drumian	~506.5
					(Stage 5)	~510
		Lower 545			(Stage 4)	~515
					(Stage 3)	~521
					(Stage 2)	~528
					Fortunian	~542
NEOPROT--EROZOIC	EDIACARAN 635					
	CRYOG--ENIAN 850					

Table 1. Stratigraphic nomenclature for the lower Paleozoic, showing currently used terminology from the International Commission on Stratigraphy (ICS) in comparison to terminology used in most previous accounts of the field trip area (DNAG time scale, Palmer, 1984). Ages refer to the base of the Epoch or Stage in question.

NOTES

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